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Towards restoring urban waters: understanding the main pressures☆

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Water bodies in the urban landscape are omnipresent, with many being small, lentic waters such as ponds and lakes. Because of high anthropogenic forcing, these systems have poor water quality, with large consequences for the provisioning of ecosystem services. Understanding of the main pressures on urban water quality is key to successful management. We identify six pressures that we hypothesize to have strong links to anthropogenic forcing including: eutrophication, aquatic invasive species, altered hydrology, altered habitat structure, climate change, and micropollutants. We discuss how these pressures may affect water quality and ecological functioning of urban waters. We describe how these pressures may interact, posing challengers for water management. We identify steps that need to be taken towards sustainable restoration, recognizing the challenges that potentially interacting pressures pose to water managers.

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Introduction

Urban waters have undergone a massive paradigm shift in recent decades from being considered as useless degraded systems, or even open sewers, to increasingly being recognized as novel and valuable ecosystems in the urban landscape [1•,2] which provide essential services for human well-being [3••,4]. Although the drivers of ecosystem change are likely very similar in urban versus natural waters, the magnitude of the pressures on water quality associated with these drivers is likely to be very different due to stronger anthropogenic forcing in urban environments. As urban waters are completely embedded in the urban landscape, pollution related to human activity is high, and alterations of morphology and hydrology are common. As a consequence, many of the lentic, often small, water bodies such as lakes, canals and ponds are heavily degraded and have a poor water quality [5,6•]. Urban water bodies may be expected to become more abundant in the near future as cities are increasingly developing green and blue infrastructure in search for nature-based solutions to, for example, storm water problems [7]. Moreover, as the urban landscape expands with 68% of people expected to live in cities by 2050 [8] more natural or rural waters will be urbanized and more new water bodies will be created within the urban landscape.

Pressures on urban waters

Currently, many urbans waters suffer from water quality issues such as toxic cyanobacterial blooms [9], fish kills due to anoxia and general deterioration of the aquatic

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habitat [10]. These unfavorable ecological conditions do not only affect the species living in the water, but also impact humans due to health hazards (toxins, pathogens) and negatively affect recreational value (swimming bans, foul odors) [11•]. However, urban water systems have been recognized as being essential for a multitude of ecosystem services [4] and beneficial to the overall resilience of the urban social-ecological system [12]. Furthermore, due to their close proximity, people interact with these water bodies on a daily basis making them relevant for the education and perception of water quality by the general public [3••,7]. It is increasingly recognized that successful restoration and management of aquatic ecosystems requires an integrated ecosystem-based approach [13–17,18•]. An essential part of this so-called systems analysis [19] is the identification and quantification of drivers and pressures (see Section 'Steps towards restoring urban waters', below).

Downing [20] outlined the ten key problems aquatic systems face (ordered on frequency of mentioning in a survey), including: first, eutrophication, second, aquatic invasive species, third, effects of altered hydrology, fourth, habitat destruction, fifth, climate change, sixth, novel chemicals or micropollutants, seventh, lost biodiversity, eight, water abstraction, ninth, overexploitation of water resources (e.g. fish) and tenth, agricultural impact. In this review, we singled out the first six problems, as we hypothesized these pressures to have strong links to increased anthropogenic forcing in the urban environment. We argue that these strong links with human activity, affect the intensity of these pressures, with often negative consequences for water quality. Below, we review for each of these pressures, how they may affect water quality and the ecological functioning of the urban water system (Table 1). We acknowledge that these pressures are likely to interact (Figure 1), with the exact nature of this interaction often not being known [21,22]. Figure 1 illustrates the myriad of potential interactions which can be found in literature, showing the enormous complexity of pressures facing our urban waters and their ecology. Despite this complexity, we attempt to identify steps that need to be taken towards sustainable restoration, while recognizing the challenges that potentially interacting pressures pose to water managers.

Eutrophication

External nutrient loading is the main driver of eutrophication, affecting primary production and thereby the rest of the food web. This has a negative impact on the ecological state of the water and its functions and services. While the response of ecological processes to eutrophication is not likely to differ in urban waters compared to rural or natural waters, the sources of the nutrient loads are markedly different [23]. From a management perspective this is essential knowledge, as restoring eutrophic systems requires insight in nutrient fluxes and therefore knowledge of its sources [24]. High nutrient loads of nitrogen (N) and phosphorus (P) may have very different pathways [25] (Figure 2), being partly attributed to land use, the runoff from construction sites [26], buildings and impervious paved surfaces [27] and leaf litter fall from planted trees [18•,28]. Human activities also contribute to eutrophication through runoff from recreational areas such as golf courses [29], feeding of ducks and other urban wildlife [18•,30], baiting and feeding by anglers [31] and sewage dumps from recreational boating [32]. The residential areas in the urban landscape also contribute strongly to the nutrient loading of urban waters, not only through wastewater flows (both treated [33] and untreated sewage water [34], including sewage and septic tank overflows [32]) but also through less obvious routes such as runoff from gardens [35•] (Figure 2h).

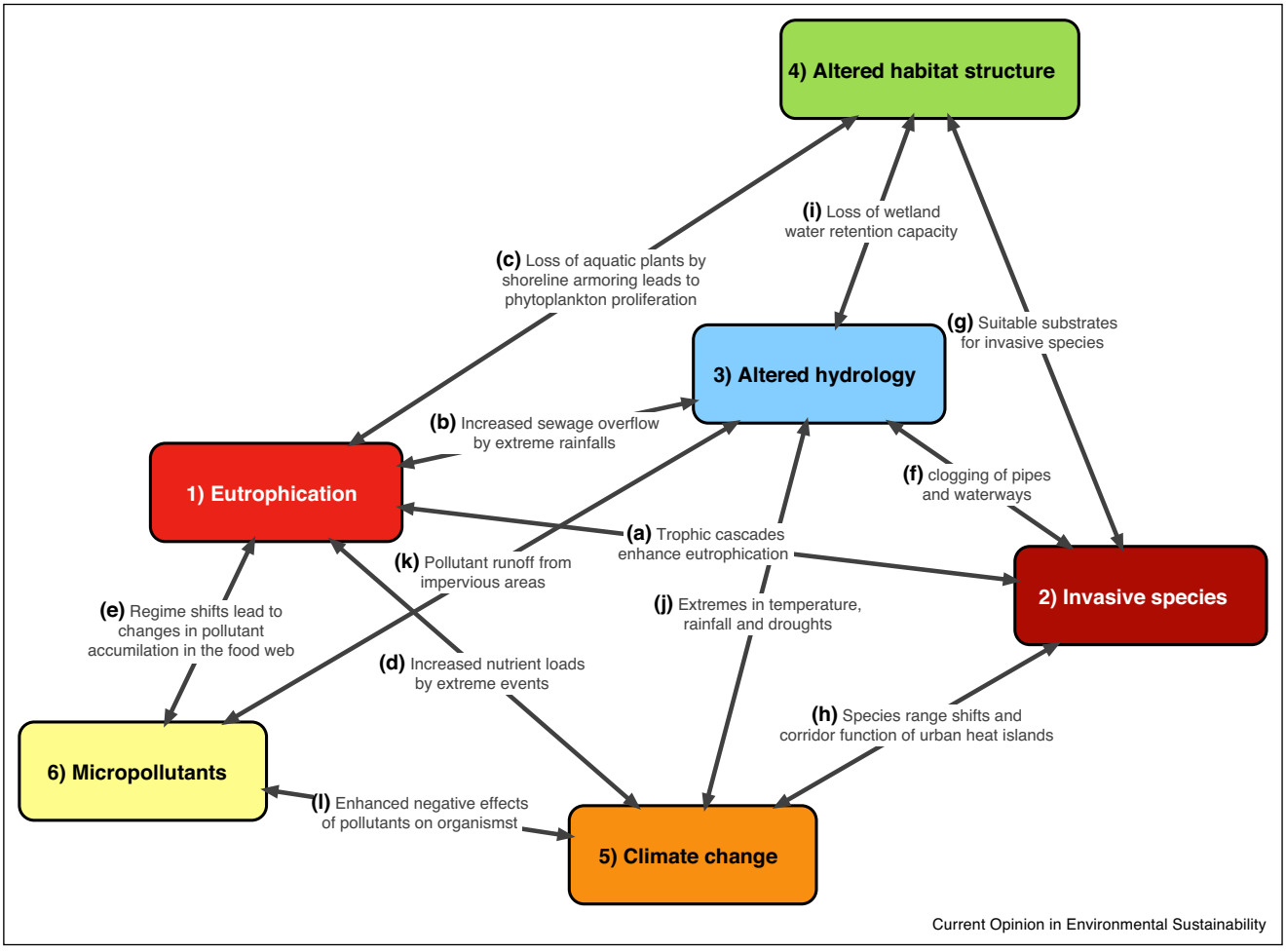
Beside high loads, it is important to note that the ratio of nitrogen to phosphorus of nutrient sources may be markedly different in urban systems depending on the landscape configuration (e.g. compare Figure 2h versus g). This may select for harmful, N-fixing cyanobacteria species [36]. Furthermore, it may also lead to a mismatch in the elemental composition of flexible primary producers and less flexible consumers [37]. This can have direct

Table 1

Estimation of the understanding and quantification of processes (e.g. nutrient sources) and ecological responses (e.g. for eutrophication: harmful blooms, dominance of aquatic weeds) for given pressures within the context of urban waters based on a literature review. With 'o' indicating a very limited understanding without thorough quantification, '+' indicating only qualitative or very limited quantitative understanding, '++' indicating a descent quantitative understanding and '+++' a very good quantitative understanding. Interactions among pressures are given (also see Figure 1) and the general direction of how to manage these pressures is outlined

Pressure	Processes	Ecological response	Interacts with	Management
1) Eutrophication	++	+++	2, 3, 4, 5	Reducing external and internal nutrient loads
2) Aquatic invasive species	+	+	1, 3, 4, 5	Eradication and containment
3) Altered hydrology	+++	++	1, 2, 4, 5, 6	Improving water storage and reducing extreme discharge events
4) Altered habitat structure	+	+	1, 2, 3	Building with nature
5) Climate change	++	+	1, 2, 3, 6	Local climate adaptation and global greenhouse gas reductions
6) Micropollutants	+	o	1, 3, 5	Improving water purification and reducing emissions

Figure 1


4) Altered habitat structure
(i) Loss of wetland water retention capacity
(c) Loss of aquatic plants by shoreline armoring leads to phytoplankton proliferation
(g) Suitable substrates for invasive species
3) Altered hydrology
(b) Increased sewage overflow by extreme rainfalls
1) Eutrophication
(f) clogging of pipes and waterways
(a) Trophic cascades enhance eutrophication
(k) Pollutant runoff from impervious areas
2) Invasive species
(e) Regime shifts lead to changes in pollutant accumilation in the food web
(j) Extremes in temperature, rainfall and droughts
(d) Increased nutrient loads by extreme events
(h) Species range shifts and corridor function of urban heat islands
6) Micropollutants
(l) Enhanced negative effects of pollutants on organismst
5) Climate change
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Interactions between the different pressures acting on urban waters.
Examples of interactions between the pressures (numbered according to their sections in the main text) are given with: a [51], b [68], c [77], d [101], e [97], f [106], g [79•], h [54], i [67], j [88], k [92], l [89].

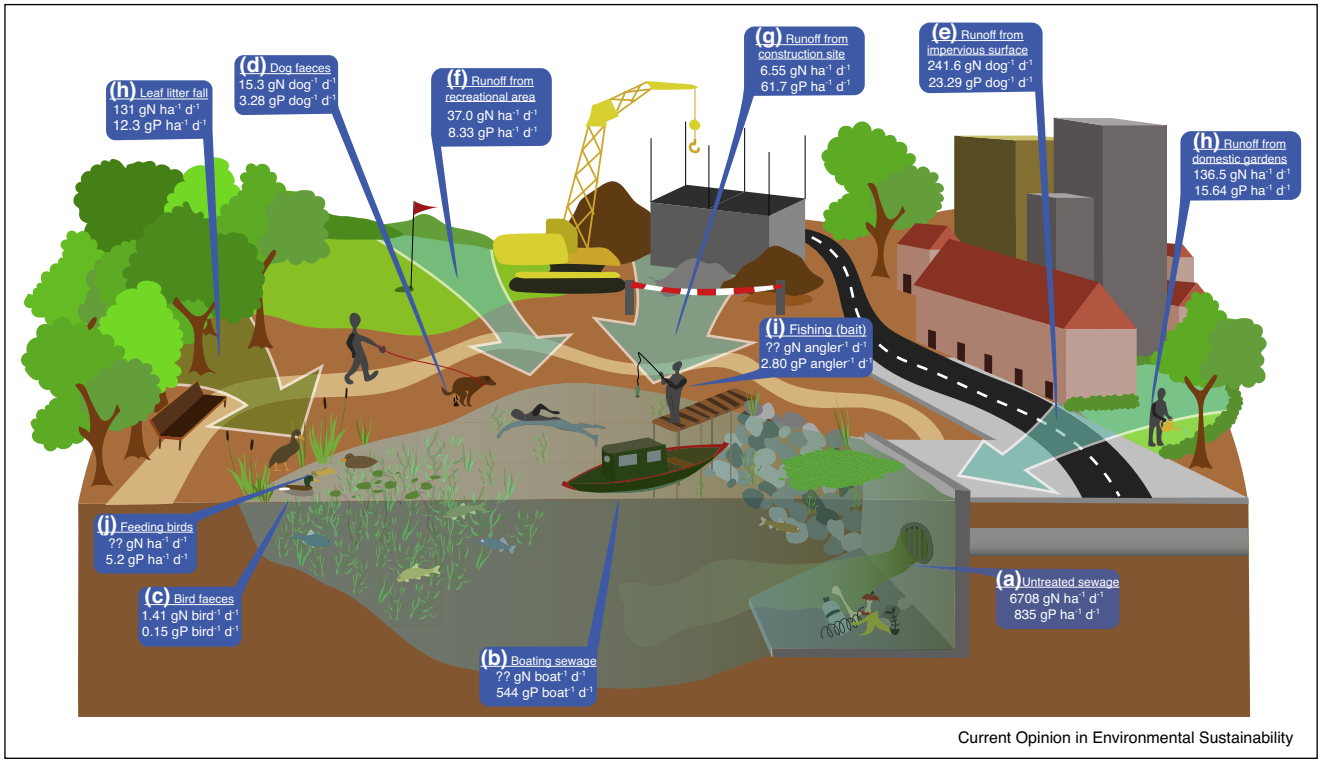
effects on community composition [38] and thereby ecological functioning.

In contrast to the nutrient sources from agricultural lands, which are largely comprised of N and P, urban nutrient sources may also contain large amounts of carbon (C) that is directly deposited into the water system (e.g. feces, sewage) [39]. These high organic loads are broken down through microbial processes, consuming oxygen in the water column and leading to periods of intense hypoxic conditions [40]. This can lead to fish kills and unpleasant odours from the water. Furthermore, high loading will stimulate microbial populations responsible for anaerobic processes, including fermentation, methanogenesis, anammox and denitrification [41], leading to increased CH_4 emissions [42,43] and increased N_2O emission in N-rich systems [44]. These high organic loads may also lead to brownification, negatively affecting the light climate, plant growth and higher trophic levels [45].

Aquatic invasive species

With high population densities, the role for humans in spreading species through the urban landscape is also much larger [2]. Humans are a primary dispersal vector of many species [46,47], both consciously [48] (e.g. aquarium, pond and garden trade) and unconsciously [49] (e.g. transfer from boats, anglers or swimmers). The dispersal capacity of species via humans has received a great deal of attention for biosecurity reasons [50], focusing on keeping invasive species out or contained. Invasive species in the aquatic environment are damaging the ecological function and impairing valued ecological services [51]. Both social and ecological network models have been applied to better understand how human movement is spreading

Figure 2


(h) Leaf litter fall
131 gN ha-1 d-1
12.3 gP ha-1 d-1
(d) Dog faeces
15.3 gN dog-1 d-1
3.28 gP dog-1 d-1
(f) Runoff from recreational area
37.0 gN ha-1 d-1
8.33 gP ha-1 d-1
(g) Runoff from construction site
6.55 gN ha-1 d-1
61.7 gP ha-1 d-1
(e) Runoff from impervious surface
241.6 gN dog-1 d-1
23.29 gP dog-1 d-1
(h) Runoff from domestic gardens
136.5 gN ha-1 d-1
15.64 gP ha-1 d-1
(i) Fishing (bait)
?? gN angler-1 d-1
2.80 gP angler-1 d-1
(j) Feeding birds
?? gN ha-1 d-1
5.2 gP ha-1 d-1
(c) Bird faeces
1.41 gN bird-1 d-1
0.15 gP bird-1 d-1
(b) Boating sewage
?? gN boat-1 d-1
544 gP boat-1 d-1
(a) Untreated sewage
6708 gN ha-1 d-1
835 gP ha-1 d-1
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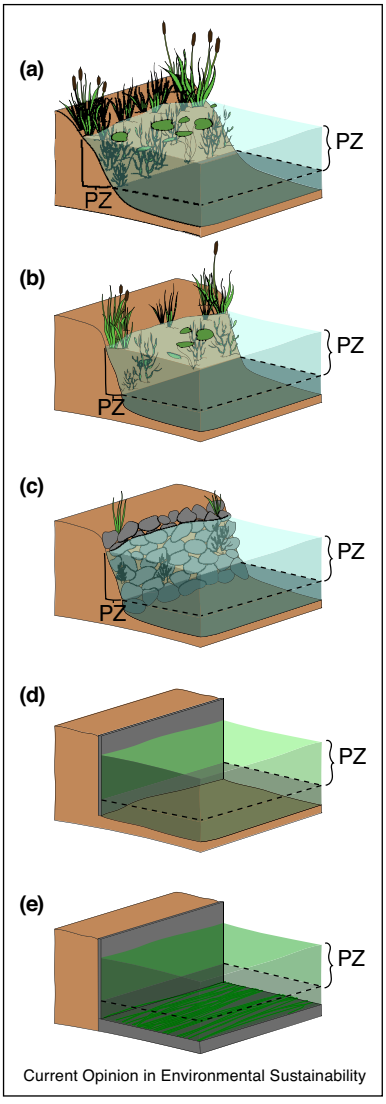
Examples of the different nutrient sources acting upon an urban lentic water.
Examples of possible loads of nitrogen (N) and phosphorus (P) loading from different sources are included in balloons (blue) originating from: a [34], b [32], c [107], d [28], e [27], f [29], g [26], h [35•], i [28] (for C:N and C:P ratios of leaf litter, multiplied with average leaf litter fall from [108]), h [31], i [18•]. Blue arrows indicate runoff from the land to the water and the green arrow refers to litter fall being washed into the water or directly blowing into the water.

species [52], with increasing interest to map the spread and movement of aquatic invasive species by using alternative data generation methods such as remote sensing [53] and crowdsourcing the general public through citizen science campaigns. In addition, the elevated temperatures in urban areas (urban heat island effect, also see Section 'Climate change'), may result in urban areas serving as corridors and habitats for heat tolerant species, such as exotic species [54,55]. The well-established threat of fish stocking to urban stagnant waters (both with invasives and native species) should not be disregarded either [56]. In many cases this fish stocking is illegal, though enforcement is often lacking. Ecological effects of the introduction of fish may be tremendous though, being the inverse equivalent of the much studied fish biomanipulation measures for restoring lakes [57]. Being part of a highly connected landscape however, is also what makes urban ponds valuable as a potential stepping stone for many species thereby contributing to regional biodiversity by facilitating movement of species through the landscape [3••].

Altered hydrology

The urban landscape with its abundance of impervious surfaces has clear effects on hydrology [58,59•]. In short, the presence of impervious surface will lead to faster runoff during rainfall (reduced lag) and more intense peak overland flows [60]. In urban environments runoff rates are higher than in natural environments due to the low ratio of water surface area versus paved and unpaved area. During rain events, these high runoff rates will lead to temporally increasing discharge and thereby flow velocity and decrease hydraulic retention time of water body as a whole. This leads to higher transport of microorganisms [61] and pollutants to the system (also see Sections 'Eutrophicationand 'Micropollutants'), but also increased flushing. Furthermore, peak discharges are exaggerated [32], causing high flow velocity which could lead to uprooting or damage to submerged plants [62] and selective washout of organisms [63,64]. The water input may also deliver extra nutrients to the system from headwaters [64] or dilute the existing dissolved nutrients if incoming water nutrient concentrations are lower than

Figure 3



Schematic representation of shoreline and water bottom modification found within urban landscapes.
For illustration purposes we assume a constant potential photic zone (dashed line, PZ). From top to bottom: **(a)** a natural shoreline with abundant riparian and submerged vegetation, **(b)** a remodeled shoreline with a steeper bank angle and less abundant vegetation, **(c)** a riprap/armored shoreline with limited potential for vegetation, **(d)** a shoreline with a retaining wall (grey), leading to lack of light on the bottom and thus no submerged plant growth, and **(e)** a system covered by hard surfaces (grey), both on the shoreline and sediment, hampering seepage dynamics and rooting of plants.

those in the receiving water body. The IPCC [65] projections on climate change (Section 'Climate change') indicated that extreme precipitation events are likely to occur more often in large parts of the world, which likely lead to higher frequency and intensity of urban run-off events. These extreme events will amplify eutrophication problems (Section 'Eutrophication') by compromising water purification potential of wetlands [66,67] and increase sewage overflows [68] into urban waters. To maintain acceptable water quality for basic human needs, urban hydrology will require intense management [69] to avoid flooding, droughts, biomass buildup and hypoxic conditions.

Altered habitat structure

Morphological alterations to urban water bodies are common, and generally entail varying forms of shoreline modifications which serve to lock water bodies in the landscape and avoid loss of land due to scouring (Figure 3). Shoreline modifications include the restructuring of shores using existing sediments, use of riprap, deposition of concrete or stone rubble to fix the shoreline in place, or placement of retaining walls. Restructuring the shoreline with existing sediment will generally change bank angles (Figure 3b), thereby affecting available habitat for plant growth [70] and associated loss of habitat gradients and species diversity. The application of riprap or armoring (Figure 3c) generally has more severe effects on littoral communities [71,72] as rooting of plants is hampered in these habitats. The retaining walls (Figure 3d) have an even more severe effect, as they remove all gradual zonation of the shoreline and thereby negatively affect light climate and hamper plant growth. The lack of vegetation negatively impacts many other biota that use these plants for food and shelter [71].

Bottom sediments may also be covered with concrete or hard rubble, further compromising ecological quality (Figure 3e). These hard substrates are common in the cases where a water body was made for a specific purpose, often drainage or water storage [73], or when lakes are filled up with building or industrial waste [74]. These concrete structures will restrict plant rooting and growth [75] and sustain growth of large biofilms, which can be composed of toxin-producing cyanobacteria, such as *Phormidium* or *Anabaena* [76]. Over time, these systems will be filled up with soft organic sediments through production and washout from the surrounding landscape. These sludge layers do not offer the required anchorage for many plants [77] and exhibit high internal nutrient release, thereby selecting for free floating species that are often deemed less desirable [78]. In addition, these stone or concrete surfaces of drainage canals or ponds provide less depth for the development of redox gradients in the sediment needed for microbial breakdown and provide substrates for invasive species [79•]. They also restrict hydrological dynamics provided by groundwater flow leading to lower diversity of microbial functions in the sediment and hampering vital ecosystem functions such as N-removal by nitrification–denitrification [80].

Climate change

Through the so-called urban heat island effect, urban landscapes are significantly warmer than the surrounding rural and natural areas [81,82]. Especially at night and during windless weather, these differences are strongest. In the context of climate change temperature increases on aquatic systems have been studied extensively, with higher temperatures leading to increased rates of biogeochemical processes [83], growth rates, phenological mismatches [84], and community shifts [85], increased chances and intensity of toxic algal blooms [86] and associated changes in ecosystem functioning. Brans and De Meester provide evidence on how urban waterfleas (*Daphnia)* are genetically adapted to higher temperatures [87]. Beside increased temperatures, both droughts and extreme rainfall are projected to increase in urban environments [66,88] which will lead to increased runoff (Section 'Altered hydrology') and higher pollutant loads to water (Sections 'Eutrophication' and 'Micropollutants') apart from the direct temperature effects on organisms. As other anthropogenic pressures are more pronounced in these waters the combined effects of climate change and other pressures may be detrimental to the ecosystem functioning of urban waters [55,66,89].

Micropollutants

The load of micropollutants in urban waters is likely high due to high human population density, increased human activity and consumption [90]. As conventional wastewater treatment plants often do not target micropollutants [91], such as pharmaceuticals, personal care products, domestic use chemicals and their metabolites, numerous pollutants have been introduced into urban aquatic systems. In addition, urban run-off and sewage overspills also cause these pollutants to directly enter the urban waters. Urban road dust, often high in trace metals such as copper, lead and zinc can be picked up by storm run-offs [92] (see Sections 'Aquatic invasive species' and 'Climate change') and thus enter the urban watershed [93]. Concentrations of these metals in densely populated areas often surpass thresholds for good water quality and ecology [93,94], and subsequently lead to impaired aquatic ecosystem functioning. As brake lining and tire wear is stronger on urban roads than on motor highways, urban dust often leads to higher contamination with heavy metals and micro plastics than motor way dust [95]. Moreover, urban waters may be undergoing increased salinization from road de-icing [96]. Apart from the direct lethal consequences of these pollutants to aquatic organisms, food web interactions may also be indirectly affected due to density shifts in different trophic groups [97], with some organisms more sensitive to pollutants than others. Often overlooked are the more subtle effects of low concentrations of pollutants on chemical communication, vital to kin recognition, foraging and mating [98•]. These multiple pollutant stressors act in concert, and may create multigenerational ecological surprises through additive, synergistic or antagonistic effects [22,99].

Steps towards restoring urban waters

Restoration of lentic water ecosystems within the urban waterscape is faced with a number of diverse challenges. An important first step is to identify the pressures that act on these urban water systems. However, from our overview it becomes clear that there is lack of knowledge of several pressures, and that interactions between these pressures likely pose challenges to water managers (Table 1). To fill the gaps, we need to better understand the impact on ecological dynamics while also quantifying the processes adequately. For example, even though the detrimental effects of eutrophication are much studied, the size of some of the nutrient sources that cause eutrophication in urban systems is poorly quantified (Figure 2), especially when human behavior is mediating nutrient inflow (duck feeding, fish baiting, dog walking). Furthermore, there is a clear need for better understanding of the ecological effects of anthropogenic pollutants in general [100•], especially in urban waters where the pollution loads are typically high.

The effectiveness of restoration measures will rely on a sound integrative analysis of all pressures in unison, taking into account the interactions and feedbacks between the ecological system and the societal one. The DPSIR (Drivers, Pressures, States, Impacts, and Responses)-model of the European Environmental Agency forms the foundation of such a system analysis, and supports water managers in the decision-making process, by advancing evidence-based management, whilst at the same time giving guidance to policy. It allows water managers to identify the operating space, in which they can develop benefit-oriented management plans. Waajen [18•] provides a noteworthy example of an ecosystem approach towards restoring urban waters. This framework of system diagnostics consists of water and nutrient budgets combined with measurements and model-based food web analysis, serving to understand how multiple pressures interact to impact water quality and ecosystem integrity at a whole. Such an approach may be expanded further by inclusion of other models such as toxicological, runoff and climate models that are linked to ecological and water quality models (e.g. [97,101]). Beside linking and bridging scientific disciplines, the connection to management practice is an important point of attention for successful restoration [102]. With the generality and exact nature of the interactions among pressures still being uncertain and possibly highly system-specific, we recommend doing full-factorial experiments on potential management approaches before attempting full-scale restoration in the field [18•]. Recognition of the lack of a silver bullet approach towards restoring urban waters by scientist and managers alike is vital, and should results in restoration plans integrating

multiple measures that target different pressures simultaneously, for example hydrology, habitat structure and eutrophication. Although pressures in urban waters may differ in magnitude from the more natural waters, the large body of knowledge available on understanding and maintaining ecosystem integrity in natural waters provides [15,16,103] an excellent starting point.

While restoration of urban waters, given their complex and interacting pressures (Figure 1, Table 1) is not an easy challenge, the rewards may be substantial in an increasingly urbanized world. Urban waters exist at a clear socio-ecological interface and can serve as an education tool for the general public on ecology and water quality [3••], which may help reconnect people to the biosphere and foster environmental stewardship [104•]. While urbanization is a major driver of global change, urban areas also concentrate the industry, knowledge and creativity needed to develop the solutions to the global sustainability challenges [104•]. Restoration of urban waters may relieve pressure on downstream areas or from areas where water is extracted and promote biodiversity [105]. In a rapidly urbanizing world with a clear need for climate proof and greener cities, creating an ecologically healthy urban waterscape will be instrumental.

Conflict of interest statement

The authors hereby declare that there are no conflicts of interest.

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